

## **Internal Waves in Straits (IWISE): Observations of Wave Generation**

David M. Farmer  
Graduate School of Oceanography (educational)  
University of Rhode Island  
Narragansett, RI 02882  
Phone: (401) 874-6222 fax (401) 874-6889 email: [dfarmer@gso.uri.edu](mailto:dfarmer@gso.uri.edu)

Jae-Hun Park  
Graduate School of Oceanography (educational)  
University of Rhode Island  
Narragansett, RI 02882  
Phone: (401) 874-6514 fax (401) 874-6728 email: [jpark@gso.uri.edu](mailto:jpark@gso.uri.edu)

Award Number: N00014-09-1-0220

### **LONG-TERM GOALS**

The long term goals are to use observations and analysis of stratified flow past complex topography to understand how internal tidal interaction in straits is responsible for the generation of large amplitude high frequency internal waves.

### **OBJECTIVES**

Our objectives are to build and deploy a 2-D array of pressure-sensor-equipped inverted echo sounders (PIESs) so as to observe the generation of internal waves by tidal interaction with topography in Luzon Strait, and to interpret the results using appropriate models of internal wave formation and evolution.

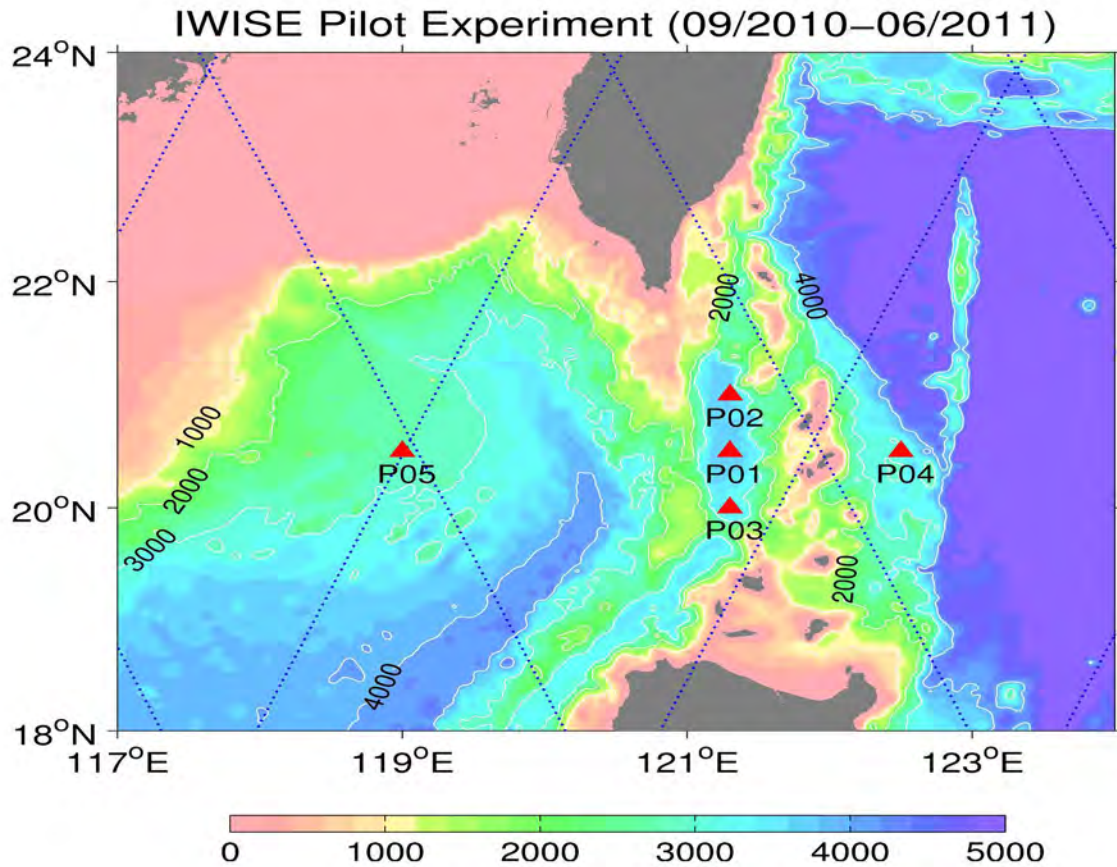
### **APPROACH**

Our approach requires construction of an array of PIESs (see Li et al. 2009). Our plan called for eight instruments, but the size of the planned array has now been increased as a result of a separate ONR-DURIP, motivating redesign of the array based on model calculations at different sections across the ridges. The plans call for a preliminary deployment of a small array, followed by a primary deployment of a full scale array.

### **WORK COMPLETED**

Model analyses of the generation region using the MITgcm have been carried out, with the goal of exploring the role of the Kuroshio in modifying the internal tide generation and resultant formation of nonlinear internal waves. Together with modeling and data analysis activities completed by former student Li Qiang under the NLIWI project (see Li et al., 2011 and Farmer et al., 2011), these results provided guidance for the array deployment. Instrument construction was carried out by the URI Equipment Development Lab.

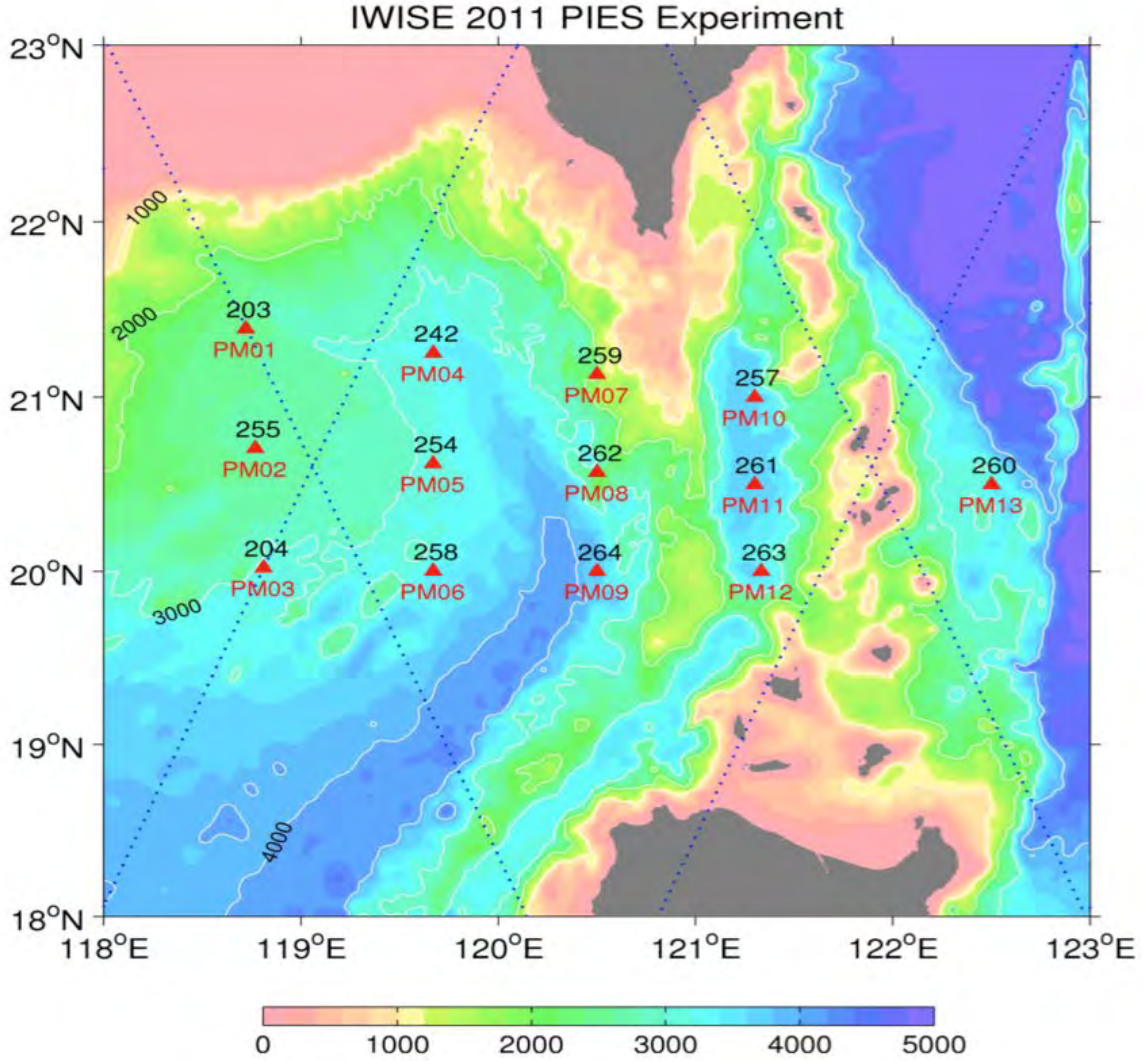
| Report Documentation Page  |                                    |                                     |  | Form Approved<br>OMB No. 0704-0188                  |                                    |
|--|------------------------------------|-------------------------------------|--|---|------------------------------------|
| Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. |                                    |                                     |  |   |                                    |
| 1. REPORT DATE<br><b>30 SEP 2011</b>   |                                    | 2. REPORT TYPE                      |  | 3. DATES COVERED<br><b>00-00-2011 to 00-00-2011</b> |                                    |
| 4. TITLE AND SUBTITLE<br><b>Internal Waves in Straits (IWISE): Observations of Wave Generation</b>   |                                    |                                     |  | 5a. CONTRACT NUMBER                                 |                                    |
|  |                                    |                                     |  | 5b. GRANT NUMBER                                    |                                    |
|  |                                    |                                     |  | 5c. PROGRAM ELEMENT NUMBER                          |                                    |
| 6. AUTHOR(S)   |                                    |                                     |  | 5d. PROJECT NUMBER                                  |                                    |
|  |                                    |                                     |  | 5e. TASK NUMBER                                     |                                    |
|  |                                    |                                     |  | 5f. WORK UNIT NUMBER                                |                                    |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><b>University of Rhode Island, Graduate School of Oceanography<br/>(educational), Narragansett, RI, 02882</b>  |                                    |                                     |  | 8. PERFORMING ORGANIZATION<br>REPORT NUMBER         |                                    |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  |                                    |                                     |  | 10. SPONSOR/MONITOR'S ACRONYM(S)                    |                                    |
|  |                                    |                                     |  | 11. SPONSOR/MONITOR'S REPORT<br>NUMBER(S)           |                                    |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br><b>Approved for public release; distribution unlimited</b>  |                                    |                                     |  |   |                                    |
| 13. SUPPLEMENTARY NOTES  |                                    |                                     |  |   |                                    |
| 14. ABSTRACT   |                                    |                                     |  |   |                                    |
| 15. SUBJECT TERMS  |                                    |                                     |  |   |                                    |
| 16. SECURITY CLASSIFICATION OF:  |                                    |                                     | 17. LIMITATION OF<br>ABSTRACT<br><br><b>Same as<br/>Report (SAR)</b> | 18. NUMBER<br>OF PAGES<br><br><b>6</b>              | 19a. NAME OF<br>RESPONSIBLE PERSON |
| a. REPORT<br><b>unclassified</b>   | b. ABSTRACT<br><b>unclassified</b> | c. THIS PAGE<br><b>unclassified</b> |  |   |                                    |



***Fig 1: Pilot study deployment of 5 pressure equipped inverted echo-sounders (P01–P05).***

A pilot cruise in September 2010 provided an opportunity for deploying a reduced array of PIES in advance of funding and construction of the full array. Five instruments were deployed in and near Luzon Strait with the assistance of Matthew Alford (U Washington) and his team (see Fig. 1). These instruments were recovered during two cruises of the Main Experiment using R/V Revelle and Ocean Researcher-3 in June-July 2011, also with assistance of Matthew Alford. During September-October 2010 all instruments provided good data, after which they were programmed to transmit at 6 second intervals, with pressure recorded every 12 seconds, for 6 months (Nov. 2010–Apr. 2011). During this longer period two instruments (P1 & P4) suffered a partial malfunction; instruments P2, P3 and P5 returned good data.

The primary array of 13 PIEs was then deployed in a more extensive array in Luzon Strait and the South China Sea (see Fig. 2). These instruments will be left in place until the spring of 2012 at which time we plan to recover them using Ocean Researcher-3 with Taiwanese assistance provided by Professor Y. J. Yang.



**Fig. 2: Primary deployment array of 13 PIES (PM01-PM13). These instruments will be recovered in the spring of 2012.**

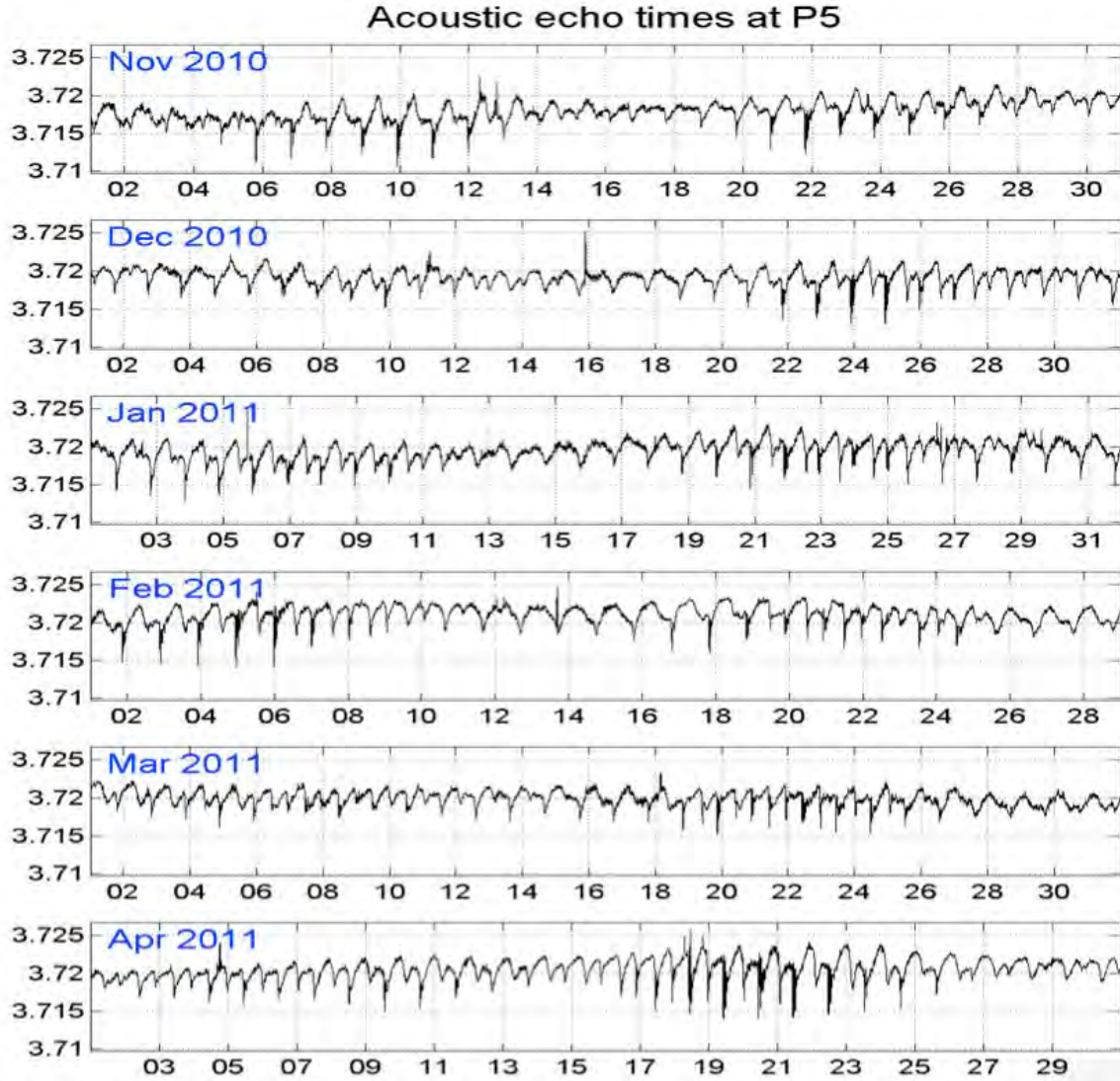
## RESULTS

Analysis of nonlinear internal waves carried out under the NLIWI program and continued into IWISE have provided results that are critical to design of the Luzon Strait deployments and will guide interpretation of results as they become available. Model calculations described in Li & Farmer (2011) explored potential mechanisms responsible for the nonlinear waves observed in the deep basin of the South China Sea. Despite the obvious nonlinearity of these waves, it appears that a reasonable first



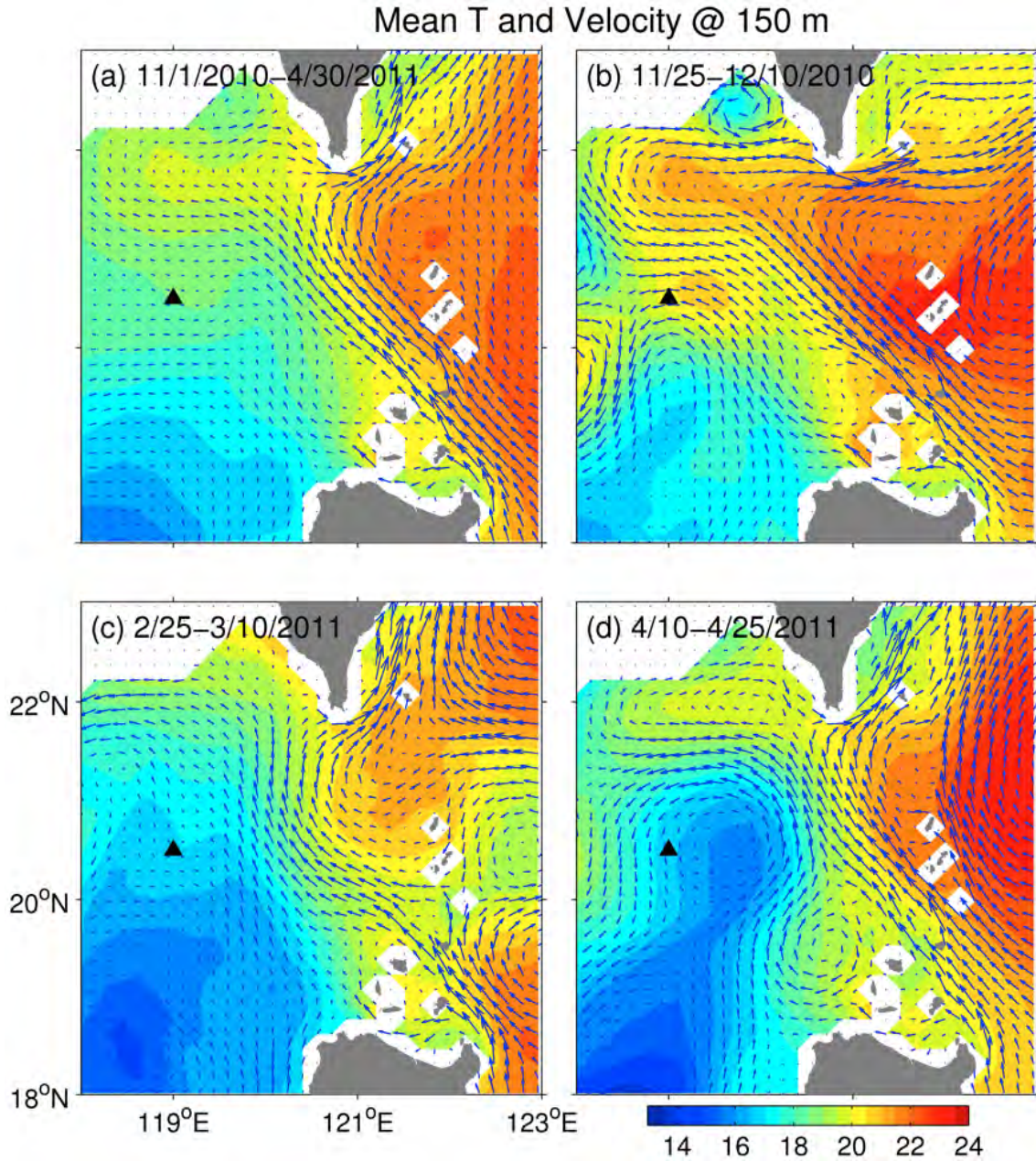
order description of their generation can be explained by a 2-layer linear model. Inverted echo sounder data from PIES can only provide information on the first internal mode, but even such a simplified representation appears to be useful in analysing the wave generation.

Doppler effects associated with a steady flow, such as might be imposed by the Kuroshio intrusion, help explain an apparent dearth of nonlinear internal waves in the winter months, when the intrusion generally occurs. Alternative explanations for lack of remotely sensed signals of nonlinear internal waves in the South China Sea in winter include the effects of higher winds causing higher sea states



***Fig. 3: A segment of the PIES time series measurements from our westernmost mooring acquired following deployment of the Pilot Study array and recovered in June/July 2011, showing internal waves generated during the winter months.***

which can obscure remotely sensed images. Since there appear to be no direct time series measurements over an extended period during winter it has not been possible to test either hypothesis. Preliminary analysis of our pilot study data reveals that energetic nonlinear internal waves exist also in the winter months (Fig. 3), supporting the latter hypothesis. However our 6-month-long inverted echo sounder measurements appear to exhibit the possible impact of the Kuroshio variability in Luzon Strait on the evolution of nonlinear interval waves in the South China Sea.



**Fig. 4: Temperature at 150m and velocity vectors derived from data-assimilated HYCOM output. (a) Averaged winter conditions (11/1/2010-4/30/2011). (b) 11/25-12/10/2010. (c) 2/25-3/10/2011. (d) 4/10-4/25/2011. The solid triangle shows the PIES location P5 used for Fig. 3.**

Mean temperature and velocity fields derived from HYCOM output during the winter months (Nov. 2010 to Apr. 2011) reveal the meandering path of the Kuroshio in Luzon Strait (Fig. 4a). While a robust interpretation will depend on appropriate model analysis and comparison with the data, these preliminary results suggest that weaker internal tides and resulting nonlinear internal waves occur when the Kuroshio intrudes into the South China Sea (Fig. 4b) or when the stratification in Luzon Strait is weakened (Fig. 4c).

## **IMPACT/APPLICATIONS**

Preliminary data from our pilot study suggest that the lack of remotely sensed signals of nonlinear internal waves in winter may be a consequence of higher sea states, which tend to obscure surface evidence of the waves. A comprehensive understanding of this issue must await analysis of data from our primary experiment.

## **RELATED PROJECTS**

ONR project – Nonlinear Internal Wave Initiative

## **REFERENCES**

- Li, Qiang, David M. Farmer, T. F. Duda, and S. R. Ramp, 2009: Acoustical measurements of nonlinear internal waves using the inverted echo sounder, *J. Atmos. Oceanic Technology*, **26**, 2228–2242.
- Li Qiang & David M Farmer, 2011: The Generation and Evolution of Nonlinear Internal Waves in the Deep Basin of the South China Sea, *J. Phys. Oceanogr.*, 41, 1345–1363.
- Farmer, D. M., M. Alford & R-C Lien, Y. J. Yang, M-H Chang & Q Li, From Luzon Strait to Dongsha Plateau: Stages in the Life of an Internal Wave, 2011, *Oceanography (in press)*.